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## (54) Pulse-based impedance measurement instrument

(57) In accordance with the present invention, a pulse-based impedance measurement instrument (10) is provided. A pulse generator (52) repetitively generates a stimulus pulse to a device under test (DUT) (50). A digitizer circuit (61), consisting of a sample-and-hold circuit (54), an analog to digital converter (56), and acquisition memory (58), repetitively samples the response voltage across the DUT to create a time record of the voltage as a function of time during a pulse re-

sponse measurement. Each time record is operated on by a Fast Fourier Transform (FFT) which converts the voltage versus time information into voltage versus frequency information in a manner well known in the art. By measuring a set of calibration resistors with known resistance values to generate a set of complex calibration constants, the impedance measurement instrument provides measurements of complex impedance and return loss versus frequency of a DUT.

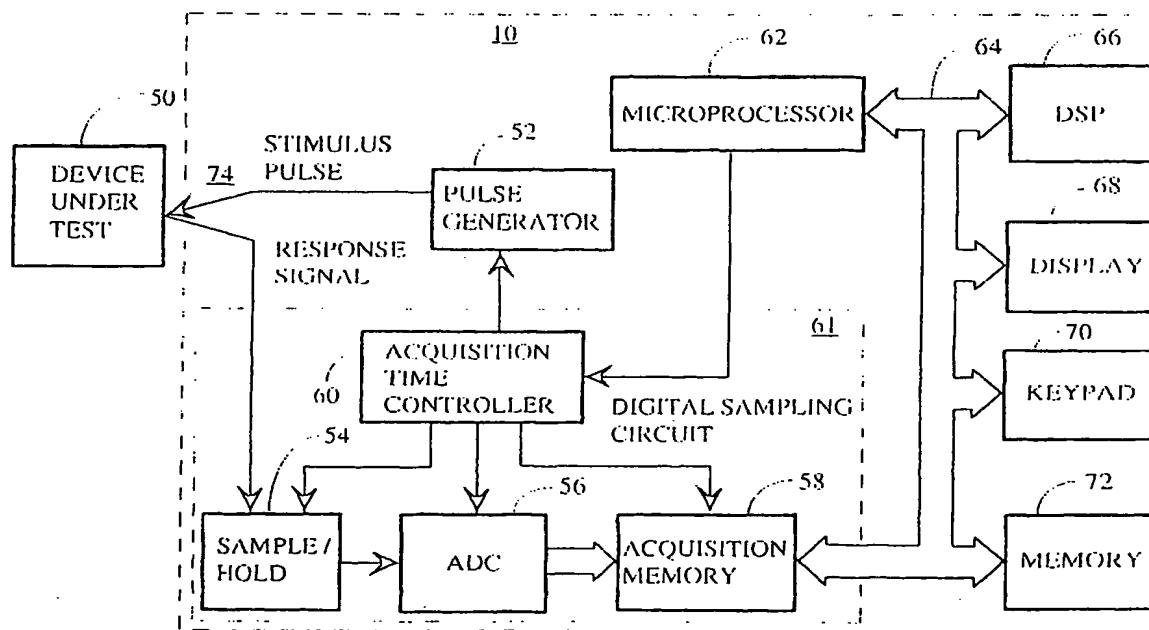


FIG. 2

ly magnitude versus time information using analog techniques. As a pulse is launched, an analog trace is swept along a horizontal display, deflected vertically by the voltage level of the reflected signal. Such traditional TDR techniques do not measure impedance versus frequency of the DUT, but rather display only its pulse response. Therefore, it would be desirable to provide a low cost, portable, pulse-based impedance measurement instrument that measures complex impedance and return loss.

### Summary of the Invention

In accordance with the present invention, a pulse-based impedance measurement instrument is provided. A pulse generator with a source resistance  $R_s$  and a peak voltage  $V_s$  is coupled to a pair of test terminals. A digitizer circuit, consisting of a sample-and-hold circuit, an analog to digital converter, and acquisition memory, creates a time record of the voltage  $V_o$  present across the test terminals during a pulse response measurement. The time record is created by repetitively generating stimulus pulses and sampling the voltage  $V_o$  of the response signal to obtain a time record with high time resolution. A time record is an array of digital measurement values stored in memory locations corresponding with the time along the original response signal. The time record thus becomes the digitally sampled equivalent of the response signal which may be used to reproduce the response signal or be converted into its frequency domain representation by a Fast Fourier Transform (FFT). The FFT, performed by a microprocessor, converts the voltage versus time information into voltage versus frequency information, the frequency domain representation, in a manner well known in the art. The frequency domain representation is maintained as a set of complex values, with real and imaginary components, to preserve the phase component of the response signal necessary to calculate complex impedance. By measuring a set of calibration resistors with known resistance values to generate a set of complex calibration constants, the impedance measurement instrument can thus provide measurements of complex impedance versus frequency.

The impedance measurement instrument is calibrated by coupling each member of a set of calibration resistors with known resistance values across the instrument connector and converting the pulse response of each calibration resistor into complex frequency domain information using a fast Fourier transform (FFT) algorithm. The set of calibration measurements now as a frequency domain representation according to the various calibration resistors represents a set of voltage values versus frequency which are used to solve for the complex calibration constants for each frequency. Thus, an entire series of linear equations, one set for each frequency, must be solved in order to obtain the complex calibration constants versus frequency. The stored cal-

ibration constants for each frequency are stored for long periods of time spanning months in the form of data arrays of complex calibration values indexed according to frequency and are updated only when the measurement instrument is re-calibrated.

5 The DUT is coupled to the instrument connector, a measurement is taken, and an FFT performed, resulting in a frequency record of response voltage versus frequency, expressed as  $V_o(f)$  where  $V_o(f)$  is a complex array of voltage values indexed according to frequency. For each frequency  $f$ , the impedance of the DUT expressed as  $Z(f)$  is calculated from  $V_o(f)$  and the associated complex calibration constants.

10 One object of the present invention is to provide a low-cost, portable impedance measurement instrument.

15 Another object of the present invention is to provide a pulse-based impedance measurement instrument that measures complex impedances over a selected range of frequencies.

20 An additional object of the present invention is to provide a method of obtaining pulse-based complex impedance measurements as a function of frequency using fast Fourier transforms.

25 Other features, attainments, and advantages will become apparent to those skilled in the art upon a reading of the following description when taken in conjunction with the accompanying drawings.

### Brief Description of the Drawings

30 FIG. 1 is an illustration of an impedance measurement instrument measuring a transmission line according to the present invention:

35 FIG. 2 is a simplified block diagram of the impedance measurement instrument of FIG. 1:

40 FIG. 3A-D are graphs illustrating the process of repetitive digital sampling to obtain a digital time record with high time resolution in the impedance measurement instrument:

45 FIG. 4A-B together comprise a flow diagram of the measurement processes of the impedance measurement instrument:

50 FIG. 5A-C are graphs that illustrate example pulse responses as contained in the time record of a 100 ohm resistor, an open circuit, and a short circuit present at the instrument terminals of the impedance measurement instrument; and

55 FIG. 6A-C are graphs that illustrate an example pulse response of a typical transmission line coupled to the impedance measurement instrument, a calculated impedance versus frequency measurement based on the transmission line pulse response, and calculated return loss versus frequency based on the impedance versus frequency measurement in the impedance measurement instrument.

present invention to convert digital time records to their frequency domain equivalents and is included in the preferred embodiment to substantially increase overall measurement speed and throughput of the measurement instrument 10.

The measurement instrument 10 is coupled to the DUT 50 via an instrument connector 74. Because the DUT 50 is often in the form of a transmission line 12 such as a twisted-pair cable, the instrument connector 74 must incorporate a means to convert the single unbalanced line which is referenced to instrument ground to a balanced line output to drive the balanced line of a twisted pair cable in a differential manner. An unbalanced-to-balanced transformer, commonly referred to as a balun (not shown), is employed in the preferred embodiment to accomplish this task.

FIG. 3A-D are graphs illustrating the process of repetitive digital sampling to obtain a digital time record of the pulse response with high time resolution. Repetitive digital sampling is employed in the present invention to obtain higher time resolution of the sampled pulse response measurements than possible with real time sampling techniques. The stimulus is repetitively generated and induced into the DUT 52 which returns a response signal which is substantially identically over each repetition. A voltage sample of each repetition of the response signal is sampled at a desired time delay from the stimulus pulse. Over multiple measurements and multiple time delays, a sampled representation of the input signal is assembled in the acquisition memory 58 in memory locations corresponding to each desired delay time to form a time record. Because the time delays may be selected with a high amount of time resolution, relatively high equivalent time sampling rates are possible. In the preferred embodiment, the time resolution of the sampled pulse response is two nanoseconds which is obtained using an ADC 56 which has a real time sample rate of four megahertz.

In FIG. 3A, a series of stimulus pulses 100 are generated by the pulse generator 52 (shown FIG. 2). For purposes of illustration, one sample trigger 102 is generated per stimulus pulse 100. The preferred embodiment of the present invention employs 16 sample triggers 102 per stimulus pulse 100. Greater or fewer sample triggers 102 may be selected depending on the desired repetition rate and available sample rate of the ADC 56. In FIG. 3B, the sample trigger 102, shown at delay times  $\Delta T_1$  -  $\Delta T_4$ , determines when the S/H 54 samples the response signal relative to the stimulus pulse. In FIG. 3C, the same response signal is received for each stimulus pulse. As shown, a total of four samples labeled SAMPLE 1 - 4 from four repetitions of response signal are taken but at different delay times  $\Delta T_1$  -  $\Delta T_4$ . In FIG. 3D, as each measurement value is collected according to the desired delay time, the measurement value is then placed in the acquisition memory 58 according to the delay time. The order in which the time delays are selected may be sequential, for exam-

ple, left to right across the acquisition memory 58, or random. Random and sequential digital sampling techniques are known in the art and either can be employed to implement the present invention.

5 FIG. 4A-B together comprise a flow diagram of the overall measurement processes of the measurement instrument 10. Process 200 labeled START begins the overall measurement process, which may be initiated automatically upon turning on the instrument 10 or 10 through an operator command via the keypad 70.

Process 210 labeled INSERT CALIBRATION RESISTOR involves coupling a calibration resistor with a known resistance value to the measurement instrument 10. Measuring a set of calibration resistors with different 15 resistance values is required in the preferred embodiment in order to provide a calibrated measurement in which the impedance of the DUT 52 may be extracted. In the preferred embodiment, the calibration of the instrument 10 is implemented as an automated sequence 20 under the control of the microprocessor 62 in which the instrument operator is prompted to insert the appropriate calibration resistor value and the measurement results are automatically stored and processed. Because the calibration resistors form the reference against 25 which the measurement instrument 10 performs the impedance measurements, the absolute accuracy of the set of calibration resistors determines the measurement accuracy of the measurement instrument 10.

In Process 220 labeled MEASURE CALIBRATION 30 PULSE RESPONSE, a calibration pulse response of a calibration resistor is measured.

In Process 230 labeled CALCULATE FFT OF CALIBRATION PULSE RESPONSE, the time record created by Process 220 is transformed into its equivalent calibration frequency domain representation using an FFT and stored in the memory 72.

In Process 235 labeled LAST CALIBRATION RESISTOR?, a decision is reached as to whether the last calibration resistor in the set has been measured. If not, 35 the Processes 210, 220, and 230 are repeated for each calibration resistor remaining in the set.

In Process 240, labeled CALCULATE CALIBRATION VALUES K(f), the calibration values for each of the frequencies f are calculated from the frequency domain representations of the pulse responses of each of the calibration resistors in the set. The calibration values are used to solve for "unknown" values in the pulse generator 52 such as source voltage and impedance using linear equations. It is because the amplitude of the stimulus pulse and the source resistance of the pulse generator are not known precisely and not controlled for over time that it is necessary to measure at least two calibration resistors of two different values which are known and controlled over time. The end result is that 40 when an unknown impedance is coupled to the instrument 10, the impedance can be calculated from the measured response signal and the calibration constants calculated from the measurements of the reference re-

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ing to the pulse response of a short circuit at the instrument connector 74. Now, a negative reflected pulse with an amplitude of 0.5 is reflected at the short circuit and returns to combine with the stimulus pulse. Note that the stimulus and reflected pulses again do not line up perfectly because the reflected pulse is delayed by approximately 5 nanoseconds as it travels through the balun and instrument connector 74. The combined pulse response appears as a separate positive stimulus pulse and negative response pulse. The pulse responses of the 100 ohm resistor in FIG. 5A and the short circuit of FIG. 5C, along with other pulse responses of calibration resistors of known values, may be employed to calculate the calibration constants used in calculating the impedance of unknown DUT's.

FIG. 6A-C are graphs that illustrate example results from the overall measurement process when an unknown DUT is coupled to the instrument connector 74. In this example, a DUT 52 in the form of a twisted wire pair transmission line 12 consisting of single segment 16 with a length of 50 feet is coupled to the impedance measurement instrument 10. The pulse response of the transmission line 12 is shown in FIG. 6A, a calculated impedance versus frequency measurement based on the transmission line pulse response and the calibration constants is shown in FIG. 6B, and the calculated return loss versus frequency based on the impedance versus frequency measurement is shown in FIG. 6C.

FIG. 6A is a pulse response measured in a manner identical to the pulse responses of FIG. 5A-C and with identical vertical and horizontal scales. In FIG. 6A, however, the DUT is no longer a lumped-element component such as a resistor or a short-circuit but is a distributed-element component in the form of a transmission line 12 where propagation time along length of the transmission line is significant. A trace 600 is the measured pulse response. The opposite end of the transmission line 12 is indicated by a small reflected pulse 602 that indicates a discontinuity caused by the connector 18. The transmission line 12 in this example is terminated at the connector 18 with a 100 ohm termination 20 which prevents further reflections from occurring. Including the termination resistor 20 is necessary to obtain an accurate return loss measurement of the transmission line 12 which does not include effects from the connector 18 which is not terminated. The graph of FIG. 6A is thus derived from the processes 250 and 260 of the flow diagram of FIG. 4A and B.

FIG. 6B is a calculated impedance versus frequency measurement based on the transmission line pulse response and the calibration constants. A trace 604 is the magnitude of the impedance, with the vertical axis in units of ohms and the horizontal axis in units of frequency in megahertz. The impedance of the transmission line is approximately 100 ohms across the frequency range spanning 100 megahertz but is subject to local peaks and valleys which are the result of reflections along the length of the transmission line 12 and from the

connectors 14 and 18. Such reflections are the result of discontinuities from the connectors 14 and 18 as was shown in the reflected pulse 602 as well as from reflections due to impedance variations along the length of the transmission line 12. The impedance is thus calculated as explained in the process 280 shown in FIG. 4B.

FIG. 6C is the calculated return loss versus frequency based on the impedance versus frequency measurement data shown in FIG. 6B. A trace 606 represents the values of the calculated return loss. Calculating return loss is done using the mathematical formula discussed in process 290 in FIG. 4B. The vertical axis is in units of decibels (dB) and the horizontal axis in units of frequency in megahertz.

It will be obvious to those having ordinary skill in the art that many changes may be made in the details of the above described preferred embodiments of the invention without departing from the spirit of the invention in its broader aspects. For example, error limits and tolerance bands may be added to the graphical display to aid in field service applications by allowing easy comparison of measurement results with specification limits. Other digital sampling techniques may be employed to build the digital time record, including techniques other than repetitive digital sampling, provided that sufficient speed and resolution are maintained. A single microprocessor may be employed to perform the FFT calculations as well as the instrument control functions to lower the overall parts count and corresponding component cost. Therefore, the scope of the present invention should be determined by the following claims.

### Claims

1. A pulse-based impedance measurement instrument, comprising:
  - (a) an instrument connector for coupling to a device under test;
  - (b) a pulse generator coupled to said instrument connector for generating stimulus pulses to said device under test;
  - (c) a digital sampling circuit coupled to said instrument connector for receiving and sampling a response signal from said device under test to provide digital measurement values;
  - (d) an acquisition memory coupled to said sampling circuit for receiving and storing said digital measurement values to form a time record of said response signal;
  - (e) a microprocessor coupled to said acquisition memory to receive said time record, wherein said microprocessor:

performs a fast Fourier transform on said time record to obtain a frequency domain representation, and

plying stimulus pulses to a device under test, acquiring a time record of the response from said device, performing a Fourier transform on the time record to obtain a frequency domain representation thereof, and calculating a set of complex impedance values of said device under test using said frequency domain representation and calibration constants derived from measurements of a set of calibration impedances.

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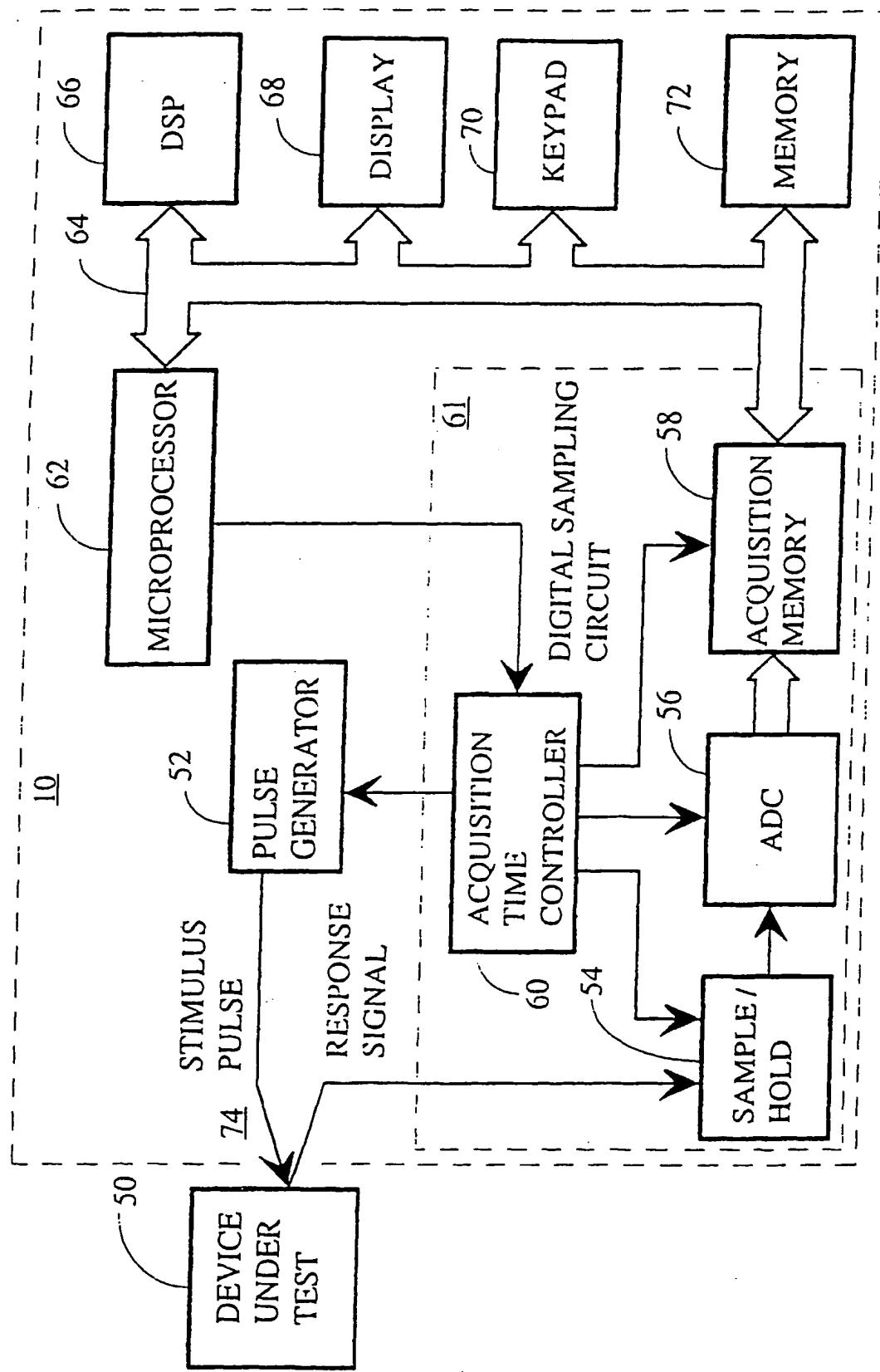


FIG. 2

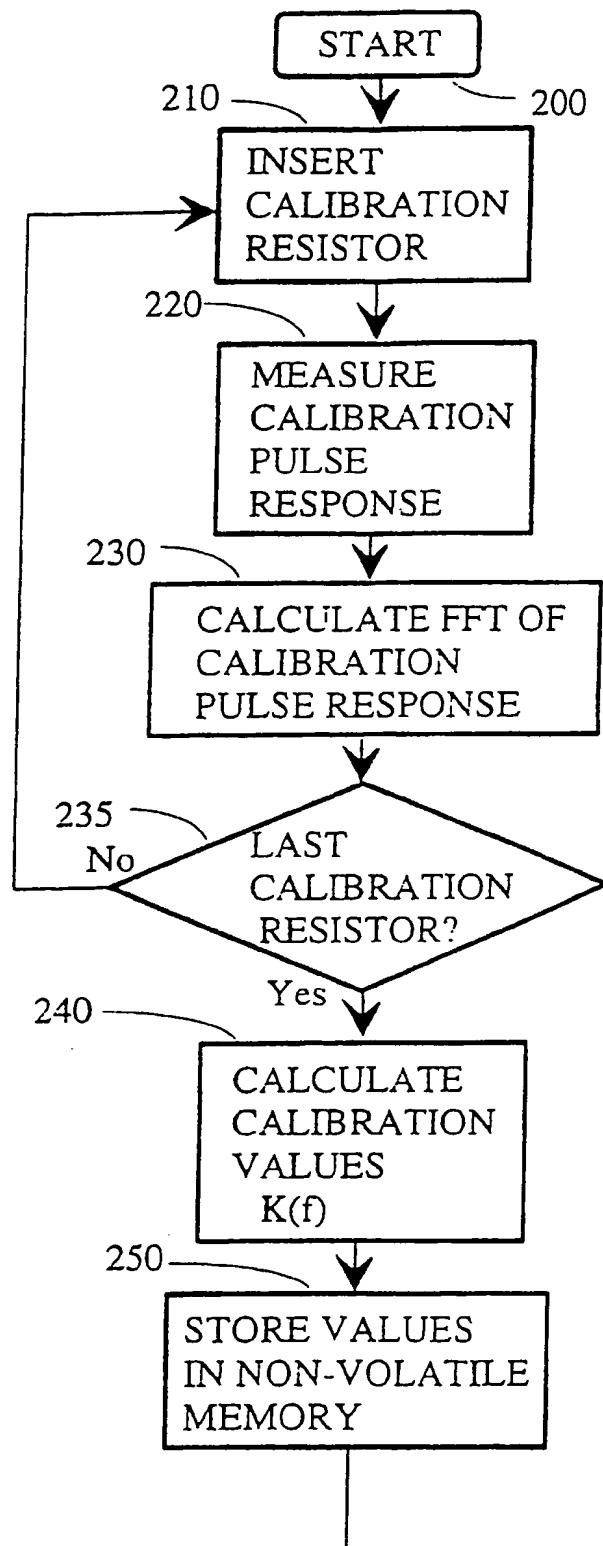


FIG. 4

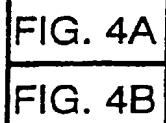


FIG. 4A

FIG. 5A

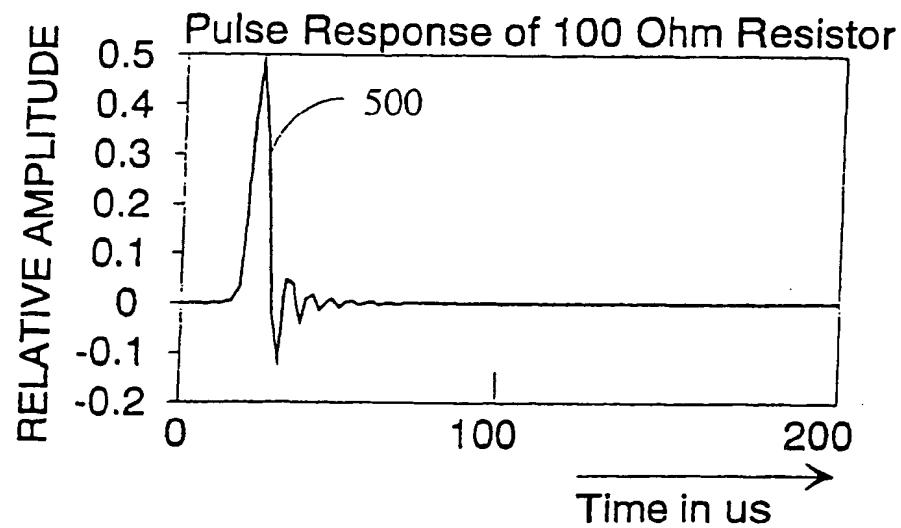


FIG. 5B

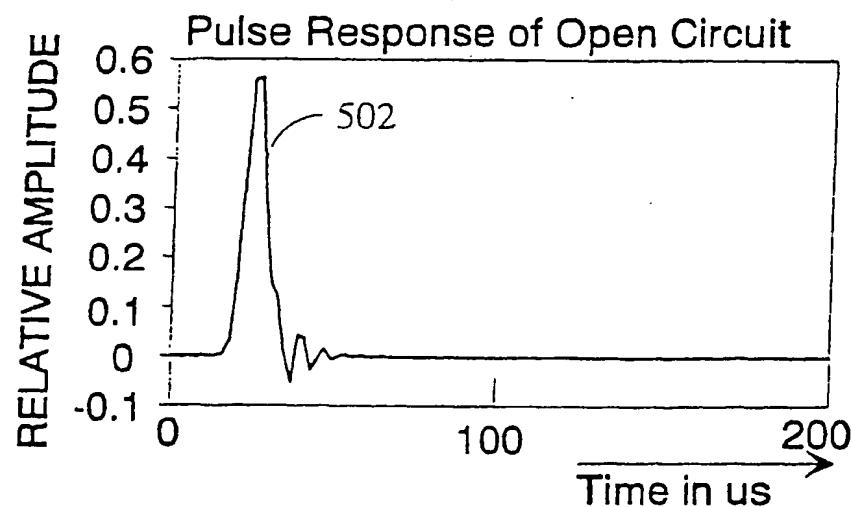
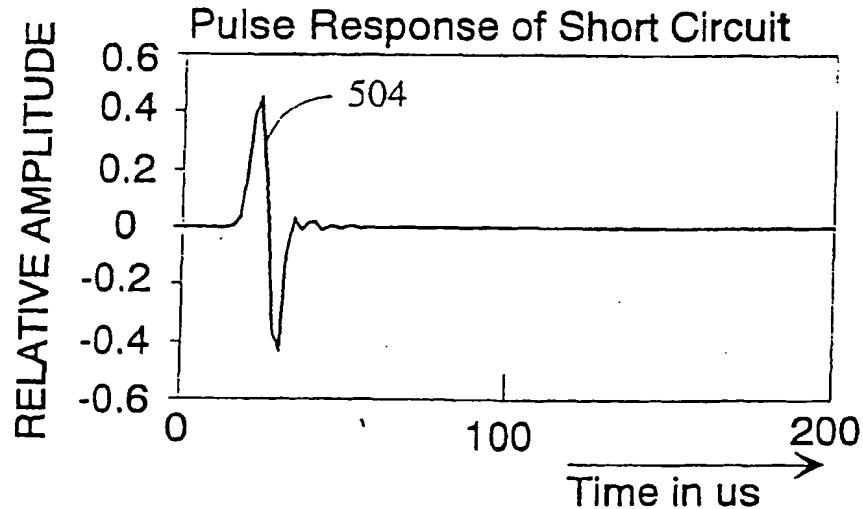


FIG. 5C





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## EUROPEAN SEARCH REPORT

Application Number  
EP 96 30 5540

DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
Y	EP-A-0 652 442 (BICC PLC) 10 May 1995 * claim 1; figure 1 * ---	1-8	G01R31/11 H04L12/26 G01R27/02
Y	US-A-4 887 041 (MASHIKIAN MATTHEW S ET AL) 12 December 1989 * column 9, line 16 - column 10, line 27 * ---	1-8	
A	US-A-4 970 466 (BOLLES DAVID C ET AL) 13 November 1990 * column 5, line 1 - line 18 * * column 6, line 16 - line 28 * * column 4, line 50 - line 59; table 1 * * column 25, line 32 - line 43 * * figures 2A,2B,4 *---	1	
A	MICROWAVE JOURNAL, vol. 30, no. 1, January 1987, US, pages 155-158,160, XP002019992 ELDON WALTERS: "Sampling Oscilloscopes for Economical High-Frequency Measurement" * figure 1 *-----	4	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			G01R H04L
The present search report has been drawn up for all claims			
Place of search	Date of completion of the search	Examiner	
BERLIN	3 December 1996	Hijazi, A	
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